Available online at www.sciencedirect.com

SCIENCE DIRECT®

Renewable and Sustainable Energy Reviews
11 (2007) 1–29

RENEWABLE
& SUSTAINABLE
ENERGY REVIEWS

www.elsevier.com/locate/rser

A review on analyzing and evaluating the energy utilization efficiency of countries

Zafer Utlu[a,*,1], Arif Hepbasli[b]

[a]Turkish Land Forces NCO Vocational College, 10110 Balikesir, Turkey
[b]Department of Mechanical Engineering, Faculty of Engineering, Ege University, 35100 Bornova, Izmir, Turkey

Received 15 December 2004; accepted 29 December 2004

Abstract

In recent years, there has been an increasing interest in applying energy and exergy analysis modeling techniques for energy-utilization assessments in order to attain energy saving. In this regard, various approaches have been used to perform the exergy analyses of countries. The main objective of the present study is to evaluate and analyze the energy utilization efficiencies of countries by reviewing the studies conducted on various countries or societies, to which different approaches have been applied. Thermodynamic relations used to perform energy and exergy analyses of countries are given first. The classification of studies conducted and the approaches applied are then investigated in terms of subsectors, such as utility, industrial, residential–commercial, and transportation sectors. Next, the countries considered are evaluated in terms of energy and exergy utilization efficiencies. Finally, the results obtained are discussed. It is expected that the review presented here will provide the investigators with knowledge about how much effective and efficient a country uses its natural resources. This knowledge is also needed for identifying energy efficiency and/or energy conservation opportunities as well as for dictating the energy strategies of a country or a society.

Keywords: Energy; Exergy; Energy efficiency; Exergy efficiency; Energy utilization; Review of energy utilization

*Corresponding author. Department of Mechanical Engineering; Faculty of Engineering; Ege University; 35100 Bornova; Izmir; Turkey. Tel.: +90 232 388 4000/Ext.: 1918-17; Fax: +90 232 388 8562.

E-mail addresses: zutlu66@yahoo.com (Z. Utlu), Hepbasli@bornova.ege.edu.tr, hepbasli@egenet.com.tr, arif.hepbasli@uoit.ca (A. Hepbasli).

[1]Tel.: +90 266 221 23 50; fax: +90 266 221 23 58.

1364-0321/$ - see front matter
doi:10.1016/j.rser.2004.12.005

Contents

1. Introduction

After the second half of the twentieth century, the industrial revolution increased the utilization of the new technological products in our daily live. This caused more consumption of the energy and made it an inseparable part of the life. Moreover, the rate of energy consumption per capita has become a criterion of success in the development for countries. Providing the growing society with the energy ceaselessly, safely and sufficiently needs to have an increasing amount of productivity and activity in this area.

Fossil fuels reserves, which provide the most part of the energy sources of the whole world, are limited and gradually decreasing. Noticing this by the large amounts of people obliged the countries to go over again their energy policy and to stop wasting it. The energy policy agenda has also changed significantly since the days of the 1973 and 1979 oil crises. Currently, it is possible to identify three policy themes related to the energy sector. These are as follows [1]: (a) the traditional energy policy agenda relating to security of energy supply, (b) concern about the environmental impact of energy, its production, transformation and use, and (c) the trend towards liberalization and the enhancement of competition in energy markets, notably in the electricity and gas sectors. This situation led

Nomenclature

ex	specific exergy (kJ/kg)
Ex	exergy (kJ)
h	specific enthalpy (kJ/kg)
I	irreversibility, exergy consumption (kJ)
IP	improvement potential for exergy (kJ)
ke	kinetic energy (kJ/kg)
m	mass (kg)
pe	potential energy (kJ/kg)
Q	heat transfer (kJ)
q	quality factor of an energy carrier
s	specific entropy (kJ/kg K)
T	temperature (K)
W	shaft work, work (kJ)

Greek letters

ε_1	energy (first law) efficiency (%)
ε_2	exergy (second law) efficiency (%)
γ_f	fuel exergy grade function
δH	enthalpy content of a particular energy carrier (kJ/kg)
μ_{j0}	chemical potentials of j components at reference state (kJ/kg)
μ_{j00}	chemical potentials of j components at dead state (kJ/kg)

Indices

0	dead state or reference environment
c	cooking
CH	chemical
d	direct
e	electrical
f	fuel
h	heating
in	input
ke	kinetic energy
KN	kinetic
o	overall
out	outlet, existing
p	product
PH	physical
PT	potential
Q	heat
r	region
rc	residential–commercial
s	stream

sh	space heating
u	utility
W	work
wh	water heating

the scientists to develop the cycling ways of the energy and to get more efficiency from the energy, which we own. New methods are about energy and exergy analysis.

The energy balance is a basic method of any process investigation. It makes the energy analysis possible, points at the needs to improve the process, is the key to optimization and is the basis to developing the exergy balance. Analysis of the energy balance results would disclose the efficiency of energy utilization in particular parts of the process and allow comparing the efficiency and the process parameters with the currently achievable values in the most modern installations. They will establish also the priority of the processes requiring consideration, either because of their excessive energy consumption or because of their particularly low efficiency.

For these reasons, the modern approach to process analysis uses the exergy analysis, which provides a more realistic view of the process. The exergy analysis is the modern thermodynamic method used as an advanced and useful tool for engineering process evaluation [2,3]. Whereas the energy analysis is based on the First Law of Thermodynamics, the exergy analysis is based on both the First and Second Laws of Thermodynamics. Both analyses utilize also the material balance for the systems considered.

The exergy of an energy form or a substance is a measure of its usefulness or quality or potential to cause change [4]. Exergy is defined as the maximum work, which can be produced by a system or a flow of matter or energy at it comes to equilibrium with a specified reference environment. Unlike energy, exergy is conserved only during ideal processes and destroyed due to irreversibilities in real processes [5].

According to Szargut et al. [2], the main purpose of exergy analysis is to discover the causes and to estimate quantitatively the magnitude of the imperfection of a thermal or chemical process. Exergy analysis leads to a better understanding of the influence of thermodynamic phenomena on the process effectiveness, comparison of the importance of different thermodynamic factors, and the determination of the most effective ways of improving the process under consideration Dincer [6] reported the linkages between energy and exergy, exergy and the environment, energy and sustainable development, and energy policy making and exergy in detail. He provided the following key points to highlight the importance of the exergy and its essential utilization in numerous ways.

- It is a primary tool in best addressing the impact of energy resource utilization on the environment.
- It is an effective method using the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the design and analysis of energy systems.
- It is a suitable technique for furthering the goal of more efficient energy-resource use, for it enables the locations, types, and true magnitudes of wastes and losses to be determined.

- It is an efficient technique revealing whether or not and by how much it is possible to design more efficient energy systems by reducing the inefficiencies in existing systems. It is a key component in obtaining sustainable development.
- It has a crucial role in energy policy-making activities.

Wall and Gong [7] summarized the historical development of the concept 'exergy', while Cengel [8] also described the meaning of exergy in daily life. He writes: "Exergy can be viewed as the *opportunities that we have* and the exergy destruction as the *opportunities wasted*. The exergy of a person in daily life can be viewed as the best job that person can do under specific conditions. The difference between the exergy of a person and the actual performance under those conditions can be viewed as the *irreversibility* or the *exergy destruction*." A true understanding of exergy and the insights it can provide into the efficiency, environmental impact and sustainability of energy systems, are required for the engineer or scientist working in the area of energy systems and the environment [9].

The method of exergy analysis has been applied to a wide variety of thermal and thermo chemical systems. A particular thermo dynamical system is the society, for example, of a country or a region [10]. Recently, there has been an increasing interest in applying energy and exergy analysis modeling techniques for energy-utilization assessments in order to attain energy saving.

The main objective of the present study is to evaluate and analyze the energy utilization efficiencies of countries by reviewing the studies conducted on various countries or societies, to which different approaches have been applied. In this regard, thermodynamic relations used to perform energy and exergy analyses of countries are given first. The classification of studies conducted and the approaches applied are then investigated in terms of subsectors, such as utility, industrial, residential–commercial, and transportation sectors. Finally, the results obtained are discussed.

2. Thermodynamic analyses of energy systems

The exergy analysis is the modern thermodynamic method used as an advanced tool for engineering process evaluation [3]. Whereas the energy analysis is based on the first law of thermodynamics, the exergy analysis is based on both the first and the second laws of thermodynamics. Both analyses utilize also the material balance for the considered system. Analysis and optimization of any physical or chemical process, using the energy and exergy concepts, can provide the two different views of the considered process. These laws are shortly explained in the subsections.

2.1. Definition of energy

The first law analysis, also referred to as energy analysis, applies the First Law of Thermodynamics (or the conservation of energy) to evaluate energy options. According to this law, energy is neither created nor destroyed in any normal physical or chemical process, but merely changed from one form to another. Because the total amount of energy remains constant, the energy lost by a system during any process equals the energy gained by the system's surrounding. Energy analysis is a basic and traditional approach to estimate various energy conversion processes. The analysis is using the concept of energy

and its conservation. The forms of energy can be expressed as enthalpy, internal energy, chemical energy, work, heat, electricity, etc.

There are several different methods of energy analysis, the principal being statistical analysis, input–output table analysis and process analysis [11]. The first method is limited by available statistical data for the whole economy or a particular industry, as well as the level of its disaggregation. Statistical analysis provides a reasonable estimate of the primary energy cost of products classified by industry. However, it cannot account for indirect energy requirements or distinguish between the different outputs from the same industry [12]. The technique of input–output table analysis, originally developed by economists, can be utilized to determine indirect energy inputs. It is only limited by the level of disaggregation in national input–output tables. Process energy analysis is the most detailed or the methods and is usually applied to a particular process or industry.

The following subsections cover some of the key aspects of thermodynamics in terms of energy and exergy balances and efficiencies, as explained elsewhere by Rosen and Dincer [13], and Dincer et al. [14–18].

2.2. Definition of exergy

The energy analysis enables energy or heat losses to be estimated, but gives no information about the optimal conversion of energy. In contrast, the Second Law of Thermodynamics shows that not all the energy input into a system can be converted into useful work. It therefore provides the basis for the definition of parameters that facilitate the assessment of the maximum amount or work achievable in a given system with different energy sources. From the thermodynamic point of view, exergy is defined as the maximum amount of work which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment. Unlike energy, exergy is not subject to a conservation law (except for ideal, or reversible, processes). Rather exergy is consumed or destroyed, due to irreversibilities in any real process. The exergy consumption during a process is proportional to the entropy created due to irreversibilities associated with the process.

The total exergy of a system Ex can be divided into four components, namely (i) physical exergy $\mathrm{Ex}^{\mathrm{PH}}$, (ii) kinetic exergy $\mathrm{Ex}^{\mathrm{KN}}$, (iii) potential exergy $\mathrm{Ex}^{\mathrm{PT}}$, and (iv) chemical exergy $\mathrm{Ex}^{\mathrm{CH}}$

$$\mathrm{Ex} = \mathrm{Ex}^{\mathrm{PH}} + \mathrm{Ex}^{\mathrm{KN}} + \mathrm{Ex}^{\mathrm{PT}} + \mathrm{Ex}^{\mathrm{CH}} \tag{1}$$

Although exergy is extensive property, it is often convenient to work with it on a unit of mass or molar basis. The total specific exergy on a mass basis may be written as follows:

$$\mathrm{ex} = \mathrm{ex}^{\mathrm{PH}} + \mathrm{ex}^{\mathrm{KN}} + \mathrm{ex}^{\mathrm{PT}} + \mathrm{ex}^{\mathrm{CH}} \tag{2}$$

Neglecting the changes in potential and kinetic energy changes as well as in the chemical composition, the specific exergy of a mass flow leads to:

$$\mathrm{ex}^{\mathrm{PH}} = (h - h_0) - T_0(s - s_0) \tag{3}$$

where h and s are the specific enthalpy and entropy, respectively, and T is the temperature, while the subscript ‘0’ denotes conditions of the reference environment.

2.3. Definition of energy and exergy efficiencies

In the analysis, it is important to understand the difference between energy and exergy efficiencies. This is essential to consider the quality and quantity of the energy used to achieve a given objective and will in fact attain efficient and effective use of energy resources (e.g. fossil fuels).

The concepts of exergy, available energy, and availability are essentially similar. The concepts of exergy destruction, exergy consumption, irreversibility, and lost work are also essentially similar. Terminology does not appear to have been standardized.

For a no steady-flow process in a system during a finite time interval, energy and exergy balances can be written as follows:

$$\text{Energy input} - \text{Energy output} = \text{Energy accumulation} \tag{4}$$

$$\text{Exergy input} - \text{Exergy output} - \text{Exergy consumption} = \text{Exergy accumulation} \tag{5}$$

In Eqs. (4) and (5), the term product might refer to shaft work or electricity developed, a certain heat transfer, some desired combination of heat and work, or possibly a particular exit stream (or streams). Losses are understood to include such things as waste heat and slack gases vented to the surroundings without use. The destruction term in the exergy equation refers to exergy destruction due to internal irreversibilities.

Energy (first law) and exergy (second law) utilization efficiencies in %, ε_1 and ε_2, can be defined as follows, respectively.

$$\varepsilon_1 = (\text{Energy in products}/\text{Total energy input})100 \tag{6}$$

$$\varepsilon_2 = (\text{Exergy in products}/\text{Total exergy input})100 \tag{7}$$

The exergy efficiency ε_2 frequently gives a finer understanding of performance than ε_1. In computing ε_1, the same weight is assigned to energy whether it becomes shaft work or a stream of low-temperature fluid. In addition, it centers attention on reducing losses to improve efficiency. The parameter ε_2 weights energy flows by accounting for each in terms of availability.

The exergy efficiencies given in Table 1 are lower than energy efficiencies, because the irreversibilities of the process destroy some of the input energy [13,19,20]. It stresses that both losses and internal irreversibilities need to be dealt with to improve performance.

Table 1
Energy and exergy efficiencies for some processes for comparison [13,19,20]

Process	Energy efficiency (%)	Exergy efficiency (%)
Residential heater (fuel)	60	9
Domestic water heater (fuel)	40	2–3
High-pressure steam boiler	90	50
Tobacco dryer (fuel)	40	4
Coal gasification (high heat)	55	46
Petroleum refining	~90	10
Steam-heated reboiler	~100	40
Blast furnace	76	46

In many cases, it is the irreversibilities that are more significant and the more difficult to deal with.

2.4. Energy and exergy balances

Assuming that flows are one-dimensional, the input and output terms in Eq. (4) are net quantities after accounting for imports and exports and the accumulation term is zero, the following may be written

$$\sum_{\text{in}} m_{\text{in}}(h + \text{ke} + \text{pe})_{\text{in}} - \sum_{\text{out}} m_{\text{out}}(h + \text{ke} + \text{pe})_{\text{out}} + \sum_{\text{r}} Q_{\text{r}} - W = 0 \tag{8}$$

where m_{in} and m_{ex} denote the mass flow across the system inlet and outlet, respectively, Q_{r} represents the heat transfer across the system boundary, W is the work (including shaft work, electricity, etc.) transferred out of the system, and h, ke and pe are the specific values of enthalpy, kinetic energy and potential energy, respectively.

Assuming that flows are one-dimensional, the input and output terms in Eq. (5) are net quantities after accounting for imports and exports and the accumulation term is zero, the following may be written

$$\sum_{\text{in}} m_{\text{in}}\text{ex}_{\text{in}} - \sum_{\text{out}} m_{\text{out}}\text{ex}_{\text{out}} + \sum_{\text{r}} \text{Ex}^{Q} - \text{Ex}^{W} - I = 0 \tag{9}$$

where ex denotes the specific exergy, Ex^{Q} and Ex^{W} are the exergy transfers associated with Q_{r} and W, respectively, while I is the system exergy consumption or irreversibility.

The exergy consumption (I) is defined as (i) $I > 0$ for an irreversible process, and (ii) $I = 0$ for a reversible process. Since $m_{\text{in}} = m_{\text{out}} = 0$, for a closed system, Eqs. (8) and (9) are simplified to:

$$\sum_{\text{r}} Q_{\text{r}} - W = 0 \tag{10}$$

$$\sum_{\text{r}} E^{Q} - E^{W} - I = 0 \tag{11}$$

2.5. Basic relations for exergy analysis

In the following subsections, some mathematical relations used in exergy analysis are summarized.

2.5.1. Exergy of a flowing stream of matter

The specific exergy of a mass flow with negligible potential and kinetic energy changes may be written as

$$ex = [(h - h_0) - T_0(s - s_0)] + \left[\sum_{j} (\mu_{j0} - \mu_{j00}) x_j\right] \tag{12}$$

where x_j denotes the mass fraction of species j, s is the specific entropy, j_0 is chemical potentials for each of the j components and the subscript 0 refers to a quantity evaluated at the dead state.

Table 2
Some characteristics of fuels used in the sectors [15,21–23]

Type of fuel	H_f (kJ/kg)	Chemical exergy, exf (kJ/kg)	γ_f
Gasoline	47,849	47,394	0.99
Natural gas	55,448	51,702	0.93
Fuel oil	47,405	47,101	0.99
Kerosene	46,117	45,897	0.99
Hard coal	25,552	26,319	1.03
Diesel fuel	39,500	42,265	1.07

2.5.2. *Exergy of heat*

The amount of thermal exergy transfer associated with heat transfer Q_r across a system boundary r at constant temperature T_r is given by

$$\mathrm{Ex}^Q = \left[1 - \left(T_0/T_r\right)\right] Q_r \tag{13}$$

2.5.3. *Exergy of work*

The exergy associated with work is as follows.

$$\mathrm{Ex}^W = W \tag{14}$$

2.5.4. *Chemical exergy*

One of the most common mass flows are hydrocarbon fuels at near-ambient condition, for which the first term in the square brackets in Eq. (12) is approximately zero, and the specific exergy reduces to chemical exergy, which can be written as

$$\mathrm{ex}_f = \gamma_f H_f \tag{15}$$

where γ_f denotes the fuel exergy grade function, defined as ratio of fuel chemical exergy to the fuel higher heating value H_f. Some typical values of H_f, γ_f and ex_f for the fuels encountered in the present study are listed in Table 2 [15,21–23]. Usually, the specific chemical exergy γ_f of a fuel at T_0 and P_0 is approximately equal to H_f. Natural gas has the highest chemical exergy value.

2.5.5. *Exergy consumption*

The amount of exergy consumed due to irreversibilities during a process is given by

$$I = T_0 S_{gen} \tag{16}$$

where S_{gen} is the entropy generation.

2.6. *Energy and exergy efficiencies for principal types of processes*

Different ways of formulating exergetic efficiency (second law efficiency, effectiveness, or rational efficiency) proposed in the literature have been given in detail elsewhere [24], while its application to a ground-source (geothermal) heat pump system is given by Hepbasli and Akdemir [25]. Among these, the rational efficiency is defined by Kotas [21,26] as the ratio

of the desired exergy output to the exergy used, namely

$$\varepsilon_2 = \frac{\mathrm{Ex}_{\mathrm{desired,output}}}{\mathrm{Ex}_{\mathrm{used}}} \tag{17a}$$

where $\mathrm{Ex}_{\mathrm{desired,output}}$ is all exergy transfer from the system, which must be regarded as constituting the desired output, plus any by-product that is produced by the system, while Exused is the required exergy input for the process to be performed.

The exergy efficiency given in Eq. (17a) may also expressed as follows [27]:

$$\varepsilon_2 = \frac{\text{desired exergetic effect}}{\text{exergy used to drive the process}} = \frac{\text{‘product’}}{\text{‘fuel’}} \tag{17b}$$

To define the exergetic efficiency both a product and a fuel for the system being analyzed are identified. The product represents the desired result of the system (power, steam, some combination of power and steam, etc.). Accordingly, the definition of the product must be consistent with the purpose of purchasing and using the system. The fuel represents the resources expended to generate the product and is not necessarily restricted to being an actual fuel such as a natural gas, oil, or coal. Both the product and the fuel are expressed in terms of exergy [28].

2.7. Exergy improvement potential

Van Gool [29] has also noted that maximum improvement in the exergy efficiency for a process or system is obviously achieved when the exergy loss or irreversibility (Exin−Exout) is minimized. Consequently, he suggested that it is useful to employ the concept of an exergetic 'improvement potential' when analyzing different processes or sectors of the economy. This improvement potential, denoted IP, is given by [11]

$$\mathrm{IP} = (1 - \varepsilon_2)(\mathrm{Ex}_{\mathrm{in}} - \mathrm{Ex}_{\mathrm{out}}) \tag{18}$$

The energy and exergy efficiencies for heating, cooling, work production, and kinetic energy production processes are tabulated in Table 3 [11,19,30]. Here, exergy efficiencies for the fuels can often be written as a function of the corresponding energy efficiencies by assuming the energy grade function to be 'unity', which is commonly valid for the fuels encountered in the present study (kerosene, gasoline, diesel and natural gas).

3. Classification of studies conducted

The method of exergy analysis has been applied to a wide variety of thermal and thermo chemical systems. A particular thermo dynamical system is the society, for example, of a country or a region according to Erteswag, 2001 [10].

The energy utilization of a country can be evaluated using exergy analysis to gain insights into its efficiency [13]. Various studies have been undertaken to analyze the sectoral energy and exergy utilization for countries (i.e. Canada, Turkey, Japan, Italy, etc.). The first one was applied by Reistad to the US in 1970, and published in 1975 [21], while the most comprehensive one in terms of years appears to be Ayres et al.'s analysis of the US between 1900 and 1998 [31].

Table 3
The energy and exergy efficiencies for heating, cooling, work production, and kinetic energy production processes [11,19,30]

Process	Energy efficiency	Exergy efficiency
Electrical heating	$\varepsilon_{1e,h} = Q_p/W_e$	$\varepsilon_{2e,h} = \mathrm{Ex}^{Q_p}/\mathrm{Ex}^{W_e}$ $\varepsilon_{2e,h} = [1-(T_0/T_p)]Q_p/W_e$ $\varepsilon_{2e,h} = [1-(T_0/T_p)]\varepsilon_{1e,h}$ $\varepsilon_{2f,h} = \mathrm{Ex}^{Q_p}/m_f\varepsilon_f$
Fuel heating	$\varepsilon_{1f,h} = Q_p/m_fH_f$	$\varepsilon_{2f,h} = [1-(T_0/T_p)]Q_p/(m_f\gamma_fH_f)$ $\varepsilon_{2f,h} = [1-(T_0/T_p)]\varepsilon_{1f,h}$ $\varepsilon_{2c,eh} = \mathrm{Ex}^{Q_p}/\mathrm{Ex}^{W_e}$
Electrical cooling	$\varepsilon_{1c,e} = Q_p/W_e$	$\varepsilon_{2c,eh} = [1-(T_0/T_p)]Q_p/W_e$ $\varepsilon_{2c,eh} = [1-(T_0/T_p)]\varepsilon_{1c,eh}$
Shaft work production via electricity	$\varepsilon_{1e,w} = W/W_e$	$\varepsilon_{2e,w} = \mathrm{Ex}^{W}/\mathrm{Ex}^{W_e} = W/W_e = \varepsilon_{1e,w}$
Shaft work production via fuel	$\varepsilon_{1e,w} = W/m_fH_f$	$\varepsilon_{2f,w} = \mathrm{Ex}^{W}/m_fH_f = W/(m_{f\gamma}H_f) = \varepsilon_{1f,w}/\gamma_f$
Fuel driven kinetic energy production	$\varepsilon_{1f,ke} = m_s\Delta ke_s/m_fH_f$	$\varepsilon_{2f,ke} = m_s\Delta ke_s/m_f\varepsilon_f = m_s\Delta ke_s/(m_f\gamma_fH_f) = \varepsilon_{1f,ke}/\gamma_{f,ke}$
Improvement potential	$\mathrm{IP} = (1-\varepsilon_2)(\mathrm{Ex}_{in}-\mathrm{Ex}_{out})$	

Note: electric and fossil fuel heating processes are taken to generate product heat Q_p at a constant temperature T_p, either from electrical energy W_e or fuel mass m_f. Double subscripts indicate the processes in which the quantity represented by the first subscript is produced by the quantity represented by the second; e.g. the double subscript h, e means heating with electricity.

3.1. Approaches used to perform exergy analyses of countries

The approaches used to analyze energy utilization of countries or societies may be grouped into three types, namely Reistad's approach, Wall's approach and Sciubba's approach [32,33].

In Reistad's approach, the end use is divided into three sectors, these names are industry, transportation and residential–commercial. In addition, energy sector with electric generation and distribution, oil refining, is treated seperatly. Flows of energy carriers for energy uses are not included in this approach.

In Wall's approach, all types of energy and material flows are considered. However, to energy carriers for energy use are considered, these flows encompass wood for construction materials and for the pulp and paper industry, harvested wood and fodder, and the products from these materials.

The so-called Sciubba's approach is relatively a new one. Extended-exergy accounting (EEA) method introduced by Sciubba was applied to the Italian society in 1996 by Milia and Sciubba [34] and recently to Norway with the figures of 2000 by Ertaswag [33]. The EEA assigns exergetic values to labor and to monetary flows within the system. Furthermore, the society EEA includes cross-flows of exergy associated with products and services transferred in the different sectors of the society. In these approaches, the system is subdivided into seven sectors, namely extraction, conversion, agriculture, industry, transportation, tertiary and domestic.

When the three approaches used are compared with each other, some differences have to be observed.

First, the subdivision into sectors is different, there are seven sectors in Sciubba's EEA approach, while end use sector is subdivided into three sectors and the utility sector is separately evaluated in Reistad's approach.

Table 4
Approaches used along with total energy and exergy efficiencies of countries [10,11,13–18,21–23,32,35–42,44–45,48]

Countries	Year analyzed	Investigators	Approach used	Total energy efficiency	Total exergy efficiency
Sweden	1920	Wall [10]	Wall's		25
Ghana	1975	Wall [35]	Wall's		28
Sweden	1980	Wall [36]	Wall's		22
Japan	1985	Wall [22]	Wall's		19
Italy	1990	Wall et al. [37]	Wall's		17
Sweden	1994	Wall [38]	Wall's		17
Norway	1995	Ertesvag and Mielnik [32]	Wall's		24
USA	1970	Reistad [21]	Reistad's	50	21
Finland	1985	Wall [35]	Reistad's		13
Canada	1986	Rosen [39]	Reistad's	50	24
Brazil	1987	Schaeffer and Wirtsch-after [40]	Reistad's	32	24
OECD	1990	Nakicenovic et al. [41]	Reistad's		12
World	1990	Nakicenovic et al. [41]	Reistad's		10
Non-OECD	1990	Nakicenovic et al. [41]	Reistad's		9
S.Arabia		1990–2001	Dincer et al. [14–18]	Reistad's	43–60
26–39					
UK		1965–1997	Hammond and Stapleton [11]	Reistad's	69–71
18–25					
Turkey	1991	Unal and Ileri [42]	Reistad's	45	24
Turkey	1993	Rosen and Dincer [13]	Reistad's	41	27
Turkey	1995	Ileri and Gurer [44]	Reistad's	35	13
Turkey	1999	Utlu and Hepbasli [48]	Reistad's	43	24
Turkey	2000	Utlu and Hepbasli [48]	Reistad's	45	25
Turkey	2001	Utlu and Hepbasli [23]	Reistad's	45	25
Turkey	2023	Utlu and Hepbasli[45]	Reistad's	57	31
Norway	2000	Ertesvag [33]	Sciubba's	47	33

Secondly, the conversions in the sectors are treated somewhat differently. In Wall's approach, useful output is accounted for whenever produced. For example, transportation, lighting, and space heating within the households contribute to the exergy output or utilization of that sector. Therefore, emphasis is put on the conversion rather than on the use and transfer of the product. In the Schubbia's approach, however, only services and products that are transferred to another sector are accounted for as output or useful products. So, the analysis of the exergy conversion provides different results in the two approaches.

3.2. Evaluating the approaches used

The approaches used to carry out energy and exergy analysis of countries as well as energy and exergy efficiency values of coutries are given in Table 4 [10,11,13–18, 21–23,32,35–42,44,45,48].

Reistad [21] published the first complete study determining both energy and exergy consumption of America during 1970. This became a pioneering study for preceding studies. Major energy consuming systems and processes are classified and typical energy and exergy efficiencies are specified for them. Weighting to their consumption, energy and exergy efficiencies of industry, residential and commercial sector and transportation were determined yielding to 50.4 and 20.9% of the country, respectively.

Reistad's approach was applied by Rosen [39] to determine energy and exergy utilization efficiencies of Canada. In this study, the Canadian energy and exergy efficiency values were calculated to be 50 and 24%, respectively. Total consumption was divided into four sectors, namely utility, residential and commercial, industrial and transportation. Utility sector was an intermediate sector supplying secondary energy to the final energy consumers. Quality factor concept was utilized to determine exergy value of incoming primary fuels. As in Reistad's study, representative energy and exergy efficiencies were used for major energy consuming systems. In case of heating and cooling applications, such as hot water heating, space heating, and refrigeration, typical temperatures were assumed to determine exergy efficiencies. Sectoral and overall efficiencies for Canada were then resolved for the year 1986. Different from other studies, industry was c1osely examined in this study. Industry was divided into subindustrial sectors, and for each sector, three temperature ranges were defined, namely low, medium, and high. Energy consumption of industry was divided into electricity and fuel. Then, energy and exergy efficiency values of industry were calculated by multiplying total energy and exergy consumptions by type with corresponding efficiency values. Energy and exergy flow diagrams were also presented for Canada for 1986.

Schaffer and Wirtschafter [40] performed energy and exergy analysis of Brazil for 1987 using a similar methodology of Reistad and Rosen. They estimated the energy and exergy efficiencies to be 32.4 and 24%, respectively. Differing from Canada and the US, input primary energy and exergy figures were given comprehensively yielding more accurate results.

Wall et al. [37] conducted a similar study for Italy using the data in 1990 This study was also different from the others in this field in that it divided the total energy and exergy consumption into two categories, namely production and tertiary sectors. Production sector was further examined in three subsectors, which were industry, transportation, and agriculture. Tertiary sector was also divided into trade, services and government. Other than determining energy consumption figures, two scenarios were suggested in the study as well. Scenario one suggested to replace fossil fuels by renewable fuels. Second scenario on the other hand suggested using optimal resources that match end-uses.

Rosen and Dincer [13] presented a method to analyze sectoral energy use of a country. They considered the energy and exergy flows through the four main economic sectors in terms of residential–commercial, industrial, transportation and utility, and applied it to Turkey. Energy and exergy analyses and hence efficiencies for the four main sectors of the Turkish economy were obtained. It was concluded that the technique presented here is useful for analyzing sectoral energy utilization, to help provide energy savings through energy efficiency and/or energy conversation measures.

Dincer et al. [14–18] applied energy and exergy modeling technique to all Saudi Arabian sectors for the period of 1990–2001. They also investigated for the first time energy and exergy utilization in the six major economic sectors of Saudi Arabia, namely residential, public and private, industrial, transportation, agricultural, and electrical utility. However,

they singly analyzed this country's economic sectors under the five studies for the period studied. In the energy and exergy analyses, the actual sectoral energy data taken from various local and international sources were used, while energy and exergy efficiencies in Saudi Arabian sectors were studied to see how efficiently energy and exergy were used in these sectors. In addition, the energy and exergy efficiencies obtained for Saudi Arabia were compared to those available for Turkey for 1993.

The studies performed on Turkey's energy and exergy analyses may be categorized as follows: (i) sectoral studies [23,30,43,45–47,49,50], (ii) Turkey's general [13,42,44,48], and (iii) Renewable energy resources [51], in all which Reistad's approach were followed. Ozdogan and Arikol [52] also applied another methodology for quantitative determinations of patterns of energy use in industry based on a nation-wide survey to characterize the structure of overall energy use in the Turkish food, textile and cement sectors. Most of these studies [23,30,42–44,46–49,51] were performed using the actual data, while some of them [45,50] were based on the projected values. The majority of the studies conducted were realized by the authors [23,30,45–51]. Among these studies, evaluating the energy utilization efficiency of Turkey's renewable energy sources [51] was noteworthy since it was one attempt in its topic. In this study, Turkey's renewable energy and exergy utilization efficiencies in 2001 were analyzed for the Turkish sectors. The total and renewable energy and exergy inputs were compared, while loses and efficiencies were identified.

Wall [53] adapted a new technique, which contributed towards a deeper understanding of the concept of exergy and increases the area of its use. The report was primarily intended for persons directly connected with energy and materials processing within business and industry. However, it was written in such a way that persons with a different background could without difficulty partake in the study and its conclusions. Detailed information such as tables and computer programs were presented in the appendices. The objective was not to describe the calculation methods in exhaustive detail, but to more concisely point out the value of this method and provide new insights and conclusions.

Wall [38] presented in detail the energy and exergy flows of two typical Swedish industries, a pulp and paper mill and a steel plant. These industries were described related to Sweden's space heating system. His study provided a short description of the price of several of the most common energy forms in terms of energy and exergy contents. Wall also reviewed the exergy concept as a tool for resource accounting and described conversions of energy and material resources in Swedish society in 1994 in terms of exergy. Necessary concepts and conventions were introduced. Exergy losses in transformations of material resources and in conversions of various forms of energy into heat are were described in some detail.

Wall [35,36] studied Japanish society using the exergy concept as a primary tool for resource accounting. Conversions of energy and material resources in Japanese society were treated in terms of exergy. Necessary concepts and conventions were introduced, while exergy losses in transformations conventions were included. Exergy losses in transformations of material resources and in conversions of various forms of energy are were given in more detail.

In a recent work, Hammond and Stapleton [11] have used the exergy method to analyze changes in the structure of the UK energy system over a period of more than 30 years from 1965. A sectoral approach was employed, with the supply side examined in terms of the main energy sources, while final demand was separated into four energy end-use groups: the domestic, service, industrial, and transport sectors. Estimates of sector weighted or

'lumped' parameters, such as exergy efficiencies, were obtained from the particular characteristics of each sector. These were employed to determine the exergetic 'improvement potential' for critical elements of the energy system. Electricity generations, together with final energy demand in the domestic sector and in transport, were shown to account for nearly 80% of the exergetic improvement potential. This poor thermodynamic performance was principally due to exergy losses in combustion and heat transfer processes associated with power generation, space heating and main transport modes. The role of the exergy method was contrasted with the various other approaches to energy technology assessment.

Ayres et al. [31] have applied the exergy analyses method to energy systems of the USA during the twentieth century. In this study, 'useful work' was defined as the product of energy (exergy) inputs multiplied by conversion efficiency. They attempted to reconstruct the useful work performed in the US economy during the twentieth century. Some economic implications were also indicated very briefly.

4. Evaluating the sectoral energy utilization efficiencies of countries

In modeling sectoral energy and exergy utilization, the present study proposes the following procedure.

(a) List energy and exergy inputs and outputs in terms of general values using energy and exergy balance relations.
(b) Subgroup the sectors into four main sectors, namely utility, industrial, commercial residential and transportation.
(c) List energy and exergy inputs and outputs in terms of sectoral values using energy and exergy balance relations.
(d) Split each subsector into its energy utilization components, such as space heating, television, etc.
(e) Calculate energy and exergy utilization values for both each and entire sector using the relations given here.
(f) Draw energy and exergy flow diagrams.
(g) Analyze the energy and exergy flow diagrams in terms of losses and energy saving opportunities and compare the efficiency values obtained with those of other countries.

4.1. Determination of energy inputs to countries

Energy systems pervade industrial societies and weave a complex web of interactions that affect the daily lives of their citizens. In order to analyze exactly the energy and environmental consequences of changes in supply and demand of energy services, it is necessary to take a holistic approach. This implies drawing the system boundary quite widely, the nation-state for policy decisions within the competence of national governments (e.g. those influencing urban transportation and air quality).

A simplified model of macro system energy flows in countries, as in Turkey, is shown in Fig. 1. Natural and renewable resources as primary energy resources and secondary derivatives such as generated electric, and import energy as fossil and electric from other countries and export energy to other countries are called energy input into the whole

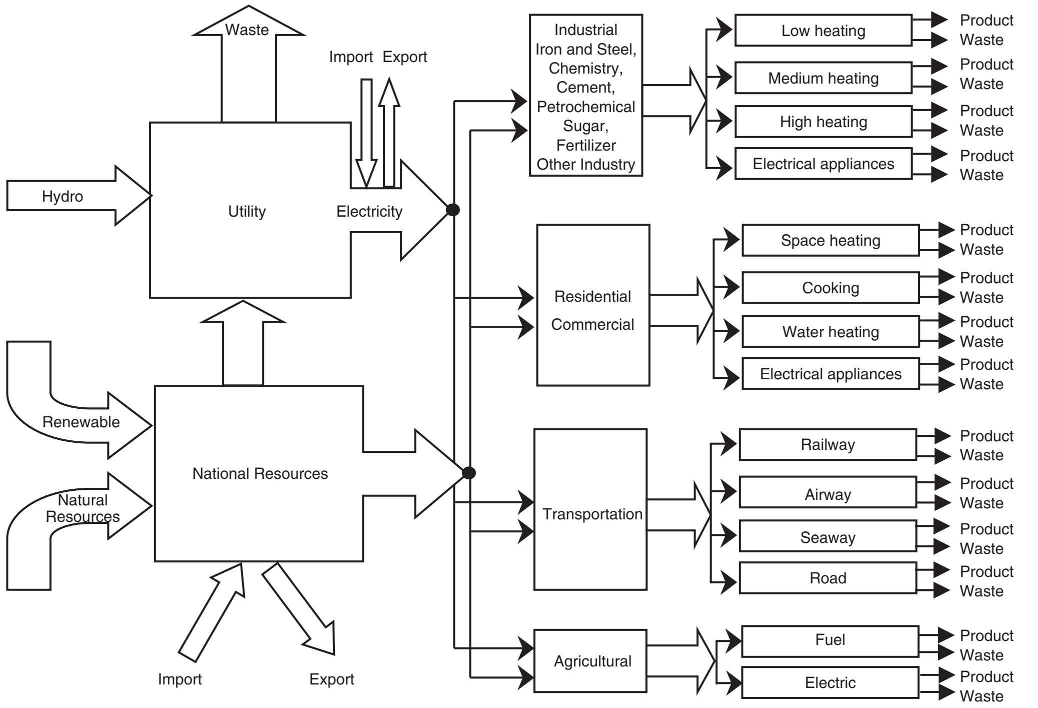

Fig. 1. An illustrative presentation of the energy flows in a macro system as country.

system of a country. Firstly, according to energy carries, determination of input energy and output energy is obligatory in application of energy and exergy modeling technique to a system or a country.

Table 5 illustrates the distribution of total energy/exergy inputs according to various energy carriers of the countries considered, while inputs to various sectors as a share of the total exergy input are shown in Table 6 [10,11,13–18,21–23,32,35–42,44–45,48]. The countries have different specialties for energy utilization; so, it may be difficult to directly narrate one to one. For example, Turkey is a developing country; UK is an industrialized country, of which industrial energy utilization is bigger than that of Turkey. In contrast, the hot climate of Saudi Arabia and Ghana requires non-significant space heating, but this case is important for Norway, Sweden and Turkey because they have cold climate.

4.2. Evaluation of the sectoral energy utilization efficiencies

4.2.1. Utility sector

Electric is a high-grade energy vector as a main source in industrialized countries. It can be used to achieve for power and heat. The three main electricity generation sources in the world are hydropower, nuclear and fossil fuels including petroleum, lignite, hard coal and natural gas. In addition, electricity is generated from thermal and renewable sources, such as biomass, geothermal, solar energy, tidal, wave and wind power. Utilization of these resources is differently displayed in countries, as shown in Table 7 where a breakdown of

Table 5
Distrubition of total energy/exergy input according to energy carriers (%) [10,11,13–18,21–23,32,35–42,44–45,48]

Country	Analyzed year	Coal	Oil	Natural gas	Wood	Hydro	Nuclear	Food	Other[a]
Sweden	1920	31	1	0	38	0	0	27	2
Ghana	1975	0	8	0	64	5	0	21	0
Sweden	1980	–	45	–	20	10	11	12	2
Japan	1985	17	50	9	3	2	10	5	3
Italy	1990	7	47	20	4	2	0	16	5
Sweden	1994	4	25	2	16	9	32	10	2
Norway	1995	5	32	0	11	41	0	10	1
USA	1970	23	38	37	0	2	0	[b]	0
Finland	1985	–	73	–	–	4	21	[b]	1
Canada	1986	13	37	28	0	14	9	[b]	0
Brazil	1987	8	34	3	40[c]	14	0	[b]	1
OECD	1990	23	42	19	4[c]	2	10	[b]	0
World	1990	25	35	18	14[c]	2	6	[b]	0
Non-OECD	1990	26	29	18	22[c]	2	0	[b]	0
S. Arabia[d]	1990–2001	0	100	0	0	0	0	[b]	0
UK[d]	1965–1997	63–14	35–34	0–42	–	1–1	1–7		0–2
Turkey	1991	27	41	7	10[c]	5	0	[b]	10
Turkey	1993	26	43	5	11[c]	9	0	[b]	6
Turkey	1995	26	46	9	12[c]	6	0	[b]	1
Turkey	1999	24	45	15	7[c]	5	0	[b]	4
Turkey	2000	26	42	16	6[c]	4	0	[b]	6
Turkey	2001	28	41	19	7[c]	3	0	[b]	2
Turkey	2023	44	22	23	1[c]	3	4	[b]	3
Norway[e]	2000	1	75	24	–	–	–		–

[a]Sun, geothermal heat, wind, imported electricty.
[b]Not included in the analysis [10].
[c]Included biomass, fuelwood and dried dung for combustion.
[d]Higher and lower values during analyzed period.
[e]Input of energy carriers to extraction sector.

total input of different energy/exergy carriers in the conversion sector is given [10,11,13–18,21–23,32,35–42,44–45,48]. In contrary, main energy carriers for electricity generation in Saudi Arabia are fossil fuels, while nuclear resources are extensively used in Finland, Sweden and Japan in the analyzed years.

To determine the performance of electricity generation sector, first, basic data sources obtained from the literature (e.g. country's energy statistics) and then the main power station types are classified, as hydroelectric, conventional steam (coal, oil, natural gas), nuclear, geothermal, wind, solar, biomass and wave. Thirdly, the energy inputs and produced electric values in these groups are used to calculate energy and exergy utilization efficiencies ($\varepsilon_{1,\mathrm{u}}$ and $\varepsilon_{2,\mathrm{u}}$) as follows, respectively [13,48].

$$\varepsilon_{1,\mathrm{u}} = \left(\frac{W_{\mathrm{out}}}{\delta H}\right)100 \tag{19}$$

$$\varepsilon_{2,\mathrm{u}} = \left(\frac{W_{\mathrm{out}}}{W_{\mathrm{in}}}\right)100 \tag{20}$$

Table 6
Input to various sectors as a share of the total exergy input [10,11,13–18,21–23,32,35–42,44–45,48]

Country	Analyzed year	Total energy sector	Utility	Industrial	Residential–commercial	Transportation	Agriculture	Food	Total end use
Sweden	1920	46	2	26	34	1		32	93
Ghana	1975	13	5	15	58	6		16	95
Sweden	1980	66	28	35	24	10		14	83
Japan	1985	88	35	37	15	14		8	74
Italy	1990	78	23	29	17	17		17	80
Sweden	1994	74	44	30	19	12		12	73
Norway	1995	80	41	35	22	16		14	87
USA	1970	100	24	29	25	26	[a]		81
Finland	1985	100	61	25	16	15	[a]		56
Canada	1986	100	34	38	24	19	[a]		81
Brazil	1987	100	18	42	21	23	[a]		87
OECD	1990	100	40	21	23	24	[a]		68
World	1990	100	31	23	31	18	[a]		71
S. Arabia[b]	1990–2001	100	22–31	60–69	5–9	26–28	9–3		85–70
UK[b]	1965–1997	100	27–37	45–25	26–30	18–35	[a]		88–90
Turkey	1991	100	26	32	38	17	5		84
Turkey	1993	100	36	52	6	32	5		88
Turkey	1995	100	26	26	31	17	5		74
Turkey	1999	100	31	25	26	16	4		71
Turkey	2000	100	32	28	28	14	5		75
Turkey	2001	100	32	28	29	15	5		77
Turkey	2023	100	29	49	23	12	5		80
Norway	2000	100	33	35	34	9	20		98

[a]This higher and lower values are input to sectors during the analyzed years.
[b]Share of Agriculture sector is in the Residential Commercial sector.

Table 7
Share of the produced electricity from energy/exergy carriers in the conversion sectors in analyzed countries [10,11,13–18,21–23,32,35–42,44–45,48]

Country	Analyzed year	Fossil	Nuclear	Hydro	Biomass	Geothermal and wind	Import	Other
Sweden	1920	0	0	100	0	0		
Ghana	1975	0	0	100	0	0	0	
Sweden	1980	11	27	61	0	0	1	
Japan	1985	62	24	14	0	0	0	
Italy	1990	71	0	14	0	1	14	
Sweden	1994	7	51	42	0	0	0	
Norway	1995	0	0	100	0	0	0	
USA	1970	81	2	17	0	0	0	
Finland	1985	33	38	22	0	0	7	
Canada	1986	19	15	66	0	0	0	
Brazil	1987	6	0.5	85	0.4	0	8	
OECD	1990	59	23	16	2	0	0	
World	1990	65	16	18	1	0		
Non-OECD	1990	71	7	21	0	0	0	
S. Arabia[a]	1990–2001	70–94	0	0	0	0	0	30–6
UKa	1965–1997	95–75	0–13	3–5	0	2	0	5
Turkey	1995	59	0	41	0.3	0.1	0	
Turkey	1999	83	0	15	1	1		
Turkey	2000	88	0	10	1	1		
Turkey	2001	80	0	18	1	1		
Turkey	2023	67	11	17	1	4		
Norway	2000	0.4	0	97.5	1.2	0	0.9	

[a]This higher and lower values are input to sectors during the analyzed years.

Thermodynamic performance of the coal-fired power stations for a US conventional design and the relationship between efficiencies for electricity generation are illustrated in Table 8 [2,11,21].

Exergy efficiencies of the analyzed countries are between 32 and 80%. Norway merely uses hydroelectricity. Therefore, it has an extremely big efficiency with 80%. However, Saudi Arabia, Turkey, Italy and USA mostly use fossil resources, so they have small efficiency with 32, 31, 37 and 36% in the analyzed year. These results are shown in Table 9 [10,11,13–18,21–23,32,35–42,44–45,48]. It should be noticed that there is no significant difference between the energy and exergy utilization efficiencies. Therefore fossil fuel and other energy inputs for power plant may all be concerned as high quality energy carriers, and consequently enthalpy (energy) and exergy input values are essentially closer. To estimate the overall energy and exergy efficiencies for the utility sector of countries, it is required to add transmission and distribution losses to the generation losses. Transmission and distribution losses within the utility sector has been estimated to be 12 and 25% of all electrical energy produced in the world [54]. This assumption of energy and exergy efficiency results will be decreased by this kind of loses.

4.2.2. Industrial sector

The industrial sector of countries consists of many industries; however, these sectors are differently indicated in every country, according to the structure of the countries.

Table 8
Thermodynamic performance of coal-fired power stations for a US conventional design (the relationship between energy and exergy efficiencies for electricity generation) [2,11,21]

Plant component	Energy losses (% of plant input)	Exergy losses (% of plant input)
Steam generator		49.0
Combustion		(29.7)
Heat exchanger	9.0	(14.9)
Thermal stack loss		(0.6)
Diffusional stack loss		(3.8)
Turbines	$=0$	4.0
Condenser	47.0	1.5
Heaters	$=0$	1.0
Miscellaneous	3.0	5.5
Plant totals	59.0	61.0
Generation efficiencies[a]	$\varepsilon_1 = 100-59 = 41$	$\varepsilon_2 = 100-61 = 39$
Power plant type	Energy-exergy efficiency relations	
Conventional steam	$\varepsilon_2 = 0.96\,\varepsilon_1$	
Combined cycle gas turbine	$\varepsilon_2 = 0.96\,\varepsilon_{1n}$	
Nuclear	$\varepsilon_2 = \varepsilon_1$	
Hydroelectric	$\varepsilon_2 = 78\%$, $\varepsilon_1 = 90\%$	

[a]Efficiencies based on the high heat value (HHV) of fuels.

Generally, significant industries are identified as namely, iron and steel, cement, chemical and petrochemical, oil and gas, sugar, fertilizer, pulp and paper, glass, ceramics, aluminum and textile. On top of that, share of the energy consumption of the end uses is rather different in industrialized societies, such as, in Norway with 46% in 1995, Italy with 42% in 1990, Turkey with 28% in 2000, in UK between 46 and 37% from 1965 to 1995, and the industrial sector being the major energy consumer. In order to simplify the analysis of energy and exergy efficiencies for this complex sector, energy consumption patterns are analyzed.

The industrial sector includes mechanical drive, process steam, direct heat and others, such as lighting, electrolytic processes and miscellaneous applications as air-conditioning for energy consumption. In order to determine energy and exergy utilization along with their efficiencies within the industrial sector, previously, industrial modes should be determined in the country. Secondly, assumptions and simplifications for the heating and mechanical processes may be made as follows: Heating processes for each industry are grouped into low, medium, and high temperature categories, as shown in Table 10 [13–19,39]. The temperature ranges given in this table are based on the work of Brown et al. [55]. The efficiencies for the medium-and high-temperature categories are obtained from Reistad [21]. All mechanical drives are assumed to have an energy efficiency value of 90% [55,56]. Thirdly, three steps are used to calculate the overall efficiency of the sector.

Initially, energy and exergy efficiencies are obtained for the process heating with each of the process temperature categories. Heating energy and exergy efficiencies averaged for the industries are then calculated using a two-step procedure: (i) weighted mean efficiencies for electrical heating and fuel heating are evaluated for each industry; and (ii) weighted mean efficiencies for all heating processes in each industry are evaluated with these values, using weighting factors as the ratio of the industry energy consumption (electric or fuel) to the total consumption of both electrical and fuel energy. Lastly, weighted mean overall

Table 9
Energy and exergy efficiencies for end-use sectors and utility [10,11,13–18,21–23,32,35–42,44–45,48]

Country	Year analyzed	Utility		Industrial		Residential–commercial		Transportation		Agriculture		Total end use	
		ε_1	ε_2	ε_1	ε_2	ε_1	ε_2	ε_1	ε_2	ε_1	ε_2	ε_1	ε_2
Sweden	1920	11	11		43		3		8a		11		25
Guana	1975	45	45		36		3		10				28
Sweden	1980	48	48		49		10		10				27
Japan	1985	37	37		41		3		10				26
Italy	1990	43	43		42		2		10				21
Sweden	1994	42	42		36		13		13				22
Norway	1995	85	85		46		11		16				27
USA	1970	36	36		41		14		20				26
Finland	1985	40	40		43		8		10				24
Canada	1986	53	53		42		15		23				30
Brazil	1987	73	73		43		12		10				26
OECD	1990	38	38		32		7		15				17
World	1990	37	37		27		5		16				15
Non-OECD	1990	37	37										9
S. Arabia	1990–2001	31–32	30–31	62–61	40–39	75–77	9–8	21–22	21–22	75–76	75–73	60–42	39–27
UK[a]	1965–1997	29–40	28–40	66–71	37–45	70–51	15–14	20–19	20–19			70–68	26–22
Turkey	1991	34	34	63	28	55	11	10	10			45	24
Turkey	1993	45	45	68	43	68	12	22	22			41	27
Turkey	1995	36	36	58	33	56	6	15	15			35	13
Turkey	1999	30	30	69	36	58	8	24	24			43	24
Turkey	2000	30	30	69	36	57	8	24	24			45	25
Turkey	2001					56	9					45	25
Turkey	2023	38	38	74	39	66	10	29	29			57	31
Norway	2000	76	76	49	50	31	3	20	19	43	45	47	33

[a]Higher and lower efficiency values during the analyzed years.

Table 10
Process heating temperatures and efficiencies for the industrial sector [13,14–19,39]

Category of process	Process temperature, T_p (°C)	Heating energy efficiencies (%)	
		Electrical $\varepsilon_{1h,e}$	Fuel $\varepsilon_{2h,f}$
Low	<120	100	655
Medium	121–399	90	60
High	>399	70	50

(heating and mechanical drive) efficiencies for each industry are evaluated using the weighting factor as the fractions of the total sectoral energy input for both heating and mechanical drives.

In the determination of sector efficiencies, weighted means for the weighted mean overall energy and exergy efficiencies for the major industries in the industrial sector are obtained, using the weighting factor as the fraction of the total industrial energy demand supplied to each industry.

Overall first and second law efficiencies ($\varepsilon_{1,\mathrm{oi}}$ and $\varepsilon_{2,\mathrm{oi}}$) for the entire industrial sector were calculated by aggregating both purchased electrical energy and direct fuel use for the Turkish industrial sector as follows [13,48].

$$\varepsilon_{1,\mathrm{oi}} = \frac{\left(\varepsilon_{1\mathrm{e}} e_{\mathrm{i}} + \varepsilon_{1\mathrm{f}} f_{\mathrm{ei}}\right)}{\left(e_{\mathrm{i}} + f_{\mathrm{ei}}\right)} \tag{21}$$

$$\varepsilon_{2,\mathrm{oi}} = \frac{\left(\varepsilon_{2\mathrm{e}} \times e_{\mathrm{i}} + \varepsilon_{2\mathrm{f}} \times f_{\mathrm{exi}}\right)}{\left(e_{\mathrm{i}} + f_{\mathrm{exi}}\right)} \tag{22}$$

Despite the fact that, it may not be completely true to compare different industries which may have completely different structures, for point of commencement, it can still give some idea to determine relative position of industries of different countries from energy and exergy utilization point of view. For instance, in 2000 Saudi Arabia with 62% energy efficiency, and 40% exergy efficiency, whereas these values are 75 and 36% in 1975 for USA, 73 and 41% in 1986 for Canada, 71, 43% in 1986 for Brazil and 68 and 35% in 2000 for Turkey, 69 and 46% in 1990 for UK. Energy and exergy efficiencies of the industrial sector in the countries considered are indicated in Table 9.

4.2.3. Residential– commercial sector

The residential–commercial sector includes space heating, water heating, cooking and electrical appliances such as, lighting, refrigeration, television, washing and dish machine, cooking appliances for energy consumption. However, commercial and institutional sector is separately analyzed, including commercial offices, education, health, hotel and, catering, retail and warehouses, as Saudi Arabia in 2001 and UK between 1965 and 1998. In the following, the utilization of energy and exergy in the RCS in the studied years is analyzed. Table 6 illustrates the use of energy and exergy this sector for the analyzed years. In these years, of country's end use energy, 23–60% was used by the residential– commercial sector. Energy utilization of this sector showed some differences in the countries considered. For instance, in Japan, the share of the energy utilization in this sector was 20% of the total exergy input to end use sector in 1985. This value was 29% in Sweden in 1980.

For determining the efficiencies of energy and exergy utilization of the residential–commercial sector, antecedently, according to energy carriers, energy inputs to this sector is obtained from country's energy statistics, in the same time, share of the energy utilization in the residential–commercial modes is delineated as Turkey: space heating with 45 and 42%, water heating with 27 and 30%, cooking with 9 and 12% and electrical appliances with 18 and 17% in the 1999 and 2000. Then, energy/exergy efficiencies of the devices for space and water heating, and cooking as well as electrical appliances in this sector can be obtained from the literature, as tabulated in Table 11 [23,30,45] or can be calculated by using relations given in Table 3. However, the ratio of saturation of the residences using devices and electrical appliances is determined from statistical census. Fourthly, mean energy and exergy efficiencies are calculated by multiplying the energy used in each end use by the corresponding efficiency for that use. The overall efficiency and effectiveness values for electrical and direct fuel uses in the residential–commercial sector are separately calculated. Finally, overall energy and exergy utilization efficiencies ($\varepsilon_{1,\mathrm{orc}}$ and $\varepsilon_{2,\mathrm{orc}}$) for the entire residential–commercial sector are calculated by aggregating both

Table 11
Efficiencies according to fuel types and components of fuel uses [23,30,45]

Fuels	Space heating		Water heating		Cooking	
	ε_1	ε_2	ε_1	ε_2	ε_1	ε_2
Coal (stove)	45	3.2	45	3.2	–	–
Coal	50	3.6			–	–
Fuel-oil	65	4.9				
Natural gas	84	6.3	80	9.6	50	10.7
L.P.G.	90	7.4	80	9.7	50	10.8
Electricity	98	7.3	90	10.8	80	17.2
Wood	35	2.5	30	3.4	22	4.5
Geothermal	54	5.3	54	5.3		
Solar			30	3.9		
Dried-dung	35	2.5	27	3.7	20	4.1

purchased electrical energy and direct fuel use for this sector as follows:

$$\varepsilon_{1,\mathrm{orc}} = \frac{\left(\varepsilon_{1e}e_{\mathrm{rc}} + \varepsilon_{1f}f_{\mathrm{erc}}\right)}{\left(e_{\mathrm{rc}} + f_{\mathrm{erc}}\right)} \tag{23}$$

$$\varepsilon_{2,\mathrm{orc}} = \frac{\left(\varepsilon_{2e} \times e_{\mathrm{rc}} + \varepsilon_{2f} \times f_{\mathrm{exrc}}\right)}{\left(e_{\mathrm{rc}} + f_{\mathrm{exrc}}\right)} \tag{24}$$

Energy and exergy efficiencies of the residential and commercial sector for the analyzed years are shown in Table 9. As clearly seen in this table, for all over the analyzed countries, energy efficiencies of the residential–commercial sector are much higher than the corresponding exergy efficiency values. This is the case because of the greater exergy loses in this sector as well as the utilization of high-temperature energy resources for relatively low-temperature applications. For example, the utilization of geothermal energy instead of the usage of fossil fuels in space heating.

4.2.4. Transportation sector

Transportation sector includes highway, rail, shipping, pipeline, and off-road transport for fuel consumption. In the following, the utilization of energy and exergy in the transportation sector in the studied years is analyzed. Table 6 illustrates the use of energy and exergy in this sector for these years. It is clear from this table that 7–23% of the end use energy of the countries considered was used by the transportation sector, although the share of this sector in this breakdown is expected to continue to decrease in the next years.

Utilization of the transportation modes varies from country to country. For example, in Turkey and Saudi Arabia, the share of the energy utilization in the transport modes is as follows: highway with 87.6 and 79.53%, railway with 2.19 and 0%, sea transport with 1.61 and 7.60% and air transport with 8.54 and 12.88% in 2000, respectively. Other example, UK transport final energy demand by end use is highway with 78.2%, railway with 2.60, sea transport with 2.40% and air transport with 16.80% in 1995. One might expect that densely population countries such as Italy (192 capita/km^2) and Japan (320 capita/km^2)

Table 12
Energy and exergy efficiencies for various transportation modes [11,14,45,50]

Modes	Efficiencies (%)
Bus and truck (Diesel)	22–28
Automobile and truck (Otto)	12–20
Air plane	15–28
Ship	32–40
Train	32–40

have more efficient transportation systems than sparsely populated countries such as Norway (11 capita/km^2), and Canada (192 capita/km^2) [10]. Petroleum products are an important energy resource with 94–98% and the remaining 4–1% was from electricity used by trains and electric streetcars, and 2–1% with solid fuel for railway in analyzed years.

For as definitely, of energy and exergy efficiencies of the transportation sector, previously, the transportation modes are determined in country. Secondly, the terms of energy and exergy use for the transportation modes are obtained from the statistical yearbook energy data. The main fuel types in the transportation sector are coal, diesel and electricity for rail, jet fuel for air, diesel and gasoline for marine, diesel and gasoline for road, and natural gas for pipelines. Then, energy/exergy efficiencies are obtained from the literature as given in Table 12 [11,14,45,50], since vehicles generally are not operated at full load, a distinction is made between rated load and operating (part load) efficiencies. Mean energy and exergy efficiencies are calculated by multiplying the energy used in each end use by the corresponding efficiency for that use. Finally, adding these values to obtain the overall efficiency of the transportation sector. Electricity and fossil fuel work production processes are taken to produce shaft work. The energy and exergy efficiencies for shaft work production from electricity and fossil fuels may be calculated using Equations given in Table 3. The weighted mean overall energy and exergy efficiencies for the entire transportation sector are also calculated using equations given in the previous section. Exergy efficiencies of the analyzed countries are between 10 and 23% in the transportation sector.

4.2.5. *Other sectors*

Other sectors are differently shown according to the preferred approaches. For instance, the agriculture sector was singly investigated in the Wall's and Scuiba's approach. However, it was evaluated within the residential sector in the Reistad's approach [21]. Besides this, Dincer [17] applied the Reistad's approach by taking into account the agriculture sector separately.

5. Results and discussion

In this study, a review on analyzing and evaluating the energy utilization efficiency of countries were presented. Energy and exergy utilization efficiencies of countries were analyzed for different sectors. The energy and exergy inputs were compared, while loses and efficiencies were identified.

The main outcomes of the energy and exergy utilization analysis are listed in Table 8, while Figs. 2 and 3 show energy and exergy efficiency diagrams for the whole of the analyzed countries, respectively. It is clear from this table that the total energy efficiencies in the analyzed years ranged from 35 to 70%, while the total exergy efficiencies varied from 15 to 39%. There were quite bigger differences between the values for these years studied.

All sectors showed considerably important and comparable loses of energy. The transportation sector constituted the biggest energy loss, followed by the utility, residential–commercial and industrial sectors. This result indicates that energy and exergy

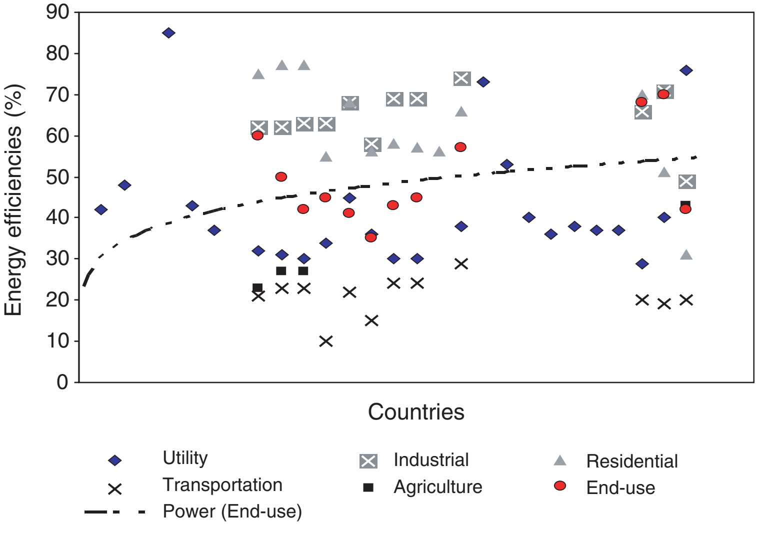

Fig. 2. Distribution of energy efficiencies of the analyzed countries.

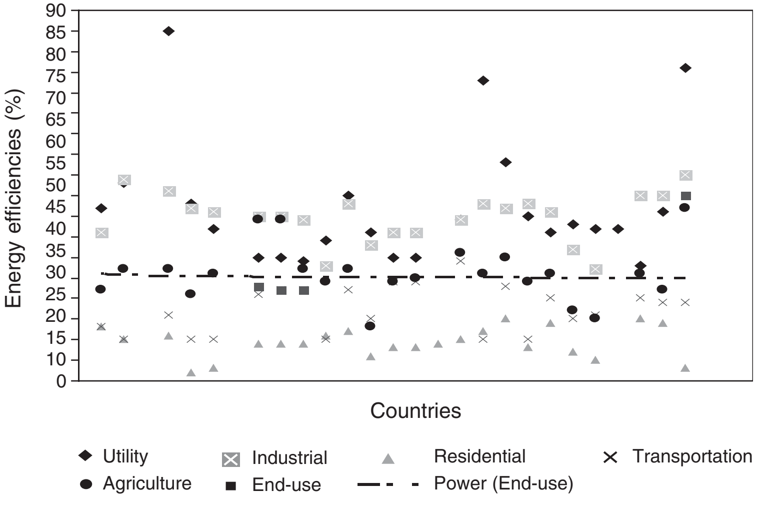

Fig. 3. Distribution of exergy efficiencies of the analyzed countries.

inefficiencies in these sectors are caused by currently available techniques used for the conversion processes. Among the subsectors studied, the industrial sector had the highest efficiencies, followed by the residential–commercial, utility and transportation sectors. Besides this, the industrial and residential–commercial sectors had about equal and high energy efficiencies, while they indicated a very poor performance in terms of their exergy efficiency values.

In terms of exergy loses, the sectors ranked rather differently. The residential–commercial sector accounted for about 85–98% of all exergy loses, followed by the transportation, utility and industrial sectors. These results indicated the need of saving the use of energy. However, habits of energy use to improve in this sector and its subsectors.

If on the other hand, the exergy approach were used by these same nations, the advantages would be obvious, because the exergy approach is able to pinpoint the true points of inefficiency within a country and clearly state that technological level within which processes and devices are operating. It allows energy planners to evaluate those feasible benefits that can be expected from future developments in energy area.

This allows policy makers to verify the real contribution of technology in the future endeavors. Of all fundamental physical considerations that enter into the determination of a coherent energy policy the easiest one to be quantitatively addresses through the application of exergy tool is the minimization of energy resources to perform given task. Therefore, the exergy approach can be applied to any country and region, and be very useful in minimizing the total energy supplied to end users. Consequently, the total environmental burden derived from energy generation and utilization.

The generalization of the exergy approach can also yield environmental benefits for these countries. Because the exergy approach allows optimizing the use of both the quantity and quality of energy carriers through the efficient matching of supply and demand, the exergy tool also allows decreasing substantially the rate of use of energy resources and the environmental burden associated with both energy production and utilization. The latter is clearly associated with the former, since a reduction of energy consumption will lead obligatory to a reduction in the rate of discharge of wastes. Because the exergy approach deals with the concept of a departure from equilibrium to the boundary environment, the exergy tool is capable of being used to estimate the pollution potential of certain wastes leaving the energy cycle as flowing out.

The exergy approach can be useful, for example, for estimating the thermal excess generated by an industrial installation, because the higher the exergy level of an emission, the higher the environmental impact that is likely to be produced. The exergy of a refuse can be given as a quantitative measure of thee quality of the effluent being released and, consequently, provide with a rough idea of its impact on the biophysical, environment and even its potential usefulness as an input for other processes.

6. Conclusions

This study indicated that exergy utilization in the analyzed countries was even worse than energy utilization. In other words, most of the countries considered represent a big potential for increasing the exergy efficiency. It is clear that a conscious and planned effort is needed to improve exergy utilization in these countries.

The implications of an energy policy are based on the analytical tool. This is because, no matter what goals are set for energy use within a country, they must obligatorily be ranked

alongside the technological, economic, social, environmental, and political costs and benefits of the results. Therefore, the energy analyst must not lose sight of the other constraints that must also be evaluated to help form a comprehensive and coherent energy policy for a country. Any policy has costs and benefits that, because they are intrinsically different in their qualitative nature, can be evaluated only in a broad political scenario.

It also may be concluded that the analyses reported here will provide the investigators with knowledge about how much effective and efficient a country uses its natural resources. This knowledge is also needed for identifying energy efficiency and/or energy conservation opportunities as well as for dictating the energy strategies of a country or a society.

References

[1] Brown S. Single-site and industrial-scale schemes. Appl Energy 1996;53:149–55.
[2] Szargut J, Morris DR, Steward FR. Exergy analysis of thermal, chemical and metallurgical processes. New York: Hemisphere Publishing Corporation; 1998.
[3] Szargut DR, Petela R. Egzergia. WNT; 1965.
[4] Rosen MA, Dincer I. On exergy and environmental impact. Int J Energy Res 1997;21:643–54.
[5] Rosen MA, Scott DS. Entropy production and exergy destruction: part I—hierarchy of Earth's major constituencies. Int J Hydrogen Energy 2003;28(12):1307–13.
[6] Dincer I. The role of exergy in energy policy making. Energy Policy 2002;30:137–49.
[7] Wall G, Gong M. On exergy and sustainable development—part 1: conditions and concepts. Exergy Int J 2001;1(3):128–45.
[8] Cengel Y. Examining the merging and splitting processes in daily life in the light of exergy. Exergy Int J 2002;2(3):128–34.
[9] Rosen MA, Dincer I. Entropy production and exergy destruction: part I—hierarchy of Earth's major constituencies. Int J Hydrogen Energy 2003;28(12):1307–13.
[10] Ertesvag IS. Society exergy analysis: a comparison of different societies. Energy 2001;26:253–70.
[11] Hammond GP, Stapleton AJ. Exergy analysis of the United Kingdom energy system. IMech—J Power Energy 2001;215:141–62.
[12] Roberts F. The aims methods and uses of energy accounting. Appl Energy 1978;4:199–217.
[13] Rosen MA, Dincer I. Sectoral energy and exergy modeling of Turkey. Trans ASME 1997;119:200–4.
[14] Dincer I, Hussain MM, Al-Zaharnah I. Energy and exergy utilization in transportation sector of Saudi Arabia. Appl Therm Eng 2004;24:525–38.
[15] Dincer I, Hussain MM, Al-Zaharnah I. Analysis of sectoral energy and exergy use of Saudi Arabia. Int J Energy Res 2004;28:205–43.
[16] Dincer I, Hussain MM, Al-Zaharnah I. Energy and exergy use in public and private sector of Saudi Arabia. Energy Policy 2004;32(14):1615–24.
[17] Dincer I, Hussain MM, Al-Zaharnah I. Energy and exergy utilization in agricultural sector of Saudi Arabia. Energy Policy 2005;33(11):1461–7.
[18] Dincer I, Hussain MM, Al-Zaharnah I. Energy and exergy use in the industrial sector of Saudi Arabia. Proc Inst Mech Engrs 2003;217:481–92.
[19] Kenny WF. Energy conversation in process industries. Orlando, FL: Academic Press; 1984.
[20] Gaggioli RA. Second law analysis for process and energy engineering. Paper presented at the AIChE Annual Meeting, IL, Nov.; 1980.
[21] Reistad GM. Available energy conversion and utilization in the United States. ASME J Eng Power 1975;97:429–34.
[22] Wall G. Exergy conversion in the Swedish society. Resour Energy 1987;9(1):55–73.
[23] Utlu Z, Hepbasli A. A Study on the evaluation of energy utilization efficiency in the Turkish residential–commercial sector using energy and exergy analysis. Energy Buildings 2003;35(11):1145–53.
[24] Cornelissen RL. Thermodynamics and sustainable development: the use of exergy analysis and the reduction of irreversibility. PhD Thesis, University of Twente, The Netherlands; 1997.

[25] Hepbasli A, Akdemir O. Energy and exergy analysis of a ground source (geothermal) heat pump system. Energy Convers Manage 2004;45(5):737–53.
[26] Kotas TJ. The exergy method of thermal plant analysis. Tiptree, Essex: Anchor Brendon Ltd; 1985.
[27] Torres EA, Gallo WLR. Exergetic evaluation of a cogeneration system in a petrochemical complex. Energy Convers Manage 1998;39(16–18):1845–52.
[28] Moran MJ. Engineering thermodynamics. In: Kreith F, editor. Mechanical engineering handbook. Boca Raton: CRC Press LLC; 1999.
[29] Van Gool W. Innovation and technology—strategies and policies. In: Soares ODD, Martins da Cruz A, Costa Pereira G, Soares IMRT, Reis AJPS, editors. Energy policy: fairly tales and factualities, 1997. p. 93– 105.
[30] Utlu Z, Hepbasli A. Analysis of energy and exergy use of the Turkish residential–commercial sector. Building Environment 2005;40:641–55.
[31] Ayres RU, Ayres LW, Warr B. Exergy, power, and work in the US economy, 1900–1998. Energy 2003;28:219–73.
[32] Ertesvag IS, Mielnik M. Exergy analysis of the Norwegian society. Energy 1995(25):957–73.
[33] Ertesvag IS. Energy, exergy, and extended-exergy analysis of the Norwegian society 2000. Energy 2005(30):645–79.
[34] Milia D, Sciubba E. Exergy-based lumped simulation of complex systems: an interactive analysis tool. In: Venere P, editor. Proceedings of the second international workshop on advanced energy studies, Italy; 2000, p. 513–23.
[35] Wall G. Exergy conversion in the Finnish, Japanese and Swedish societies, Report, Turku (Finland): Turku School of Economics; 1991.
[36] Wall G. Exergy conversion in the Japanese society. Energy 1990;15(5):435–44.
[37] Wall G, Sciubba E, Naso V. Exergy use in the Italian society. Energy 1994;19(12):1267–74.
[38] Wall G. Exergy use in the Swedish society 1994. Proceedings of international conference on thermodynamic analysis and improvement of energy systems (TAIES'97), Beijing (China), 10–13 June, 1997 (http://www.exergy.se).
[39] Rosen MA. Evaluation of energy utilization efficiency in Canada using energy and exergy analyses. Energy 1992;17(4):339–50.
[40] Schaeffer R, Wirtschafter RM. An exergy analysis for the Brazilian economy: from energy production to final energy use. Energy 1992;17(9):841–55.
[41] Nakicenovic N, Gilli PV, Kurz R. Regional and global exergy and energy efficiencies. Energy 1996; 21(3):323–37.
[42] Unal A. Energy and exergy balance for Turkey in 1991. MSc Thesis, University of Middle East Technical University, Ankara, Turkey; 1994.
[43] Ertay S. Energy and exergy utilization in Turkish residential and commercial sector. MSc Thesis, University of Middle East Technical University, Ankara, Turkey; 1997.
[44] Ileri A, Gurer T. Energy and exergy utilization in turkey during 1995. Energy 1998;23(12):1099–106.
[45] Utlu Z. Analysis of Turkey's sectoral energy and exergy utilization efficiency by 2023. PhD Thesis in Solar Energy Institute (Advisor: A. Hepbasli), Graduate School of Natural and Applied Sciences, Ege University, Izmir, Turkey; 2003 [in Turkish].
[46] Utlu Z, Hepbasli A. Comparison of Turkey's sectoral energy utilization efficiencies between 1990 and 2000: part 1. utility and industrial sectors. Energy Sources 2003;26:1331–44.
[47] Hepbasli A, Utlu Z. Comparison of Turkey's sectoral energy utilization efficiencies between 1990 and 2000: part 2. residential–commercial and transportation sectors. Energy Sources 2003;26:1345–55.
[48] Utlu Z, Hepbasli A. Turkey's sectoral energy and exergy analysis between 1999 and 2000. Int J Energy Res 2004;28:1176–96.
[49] Utlu Z, Hepbasli A. Estimating the energy and exergy utilization efficiencies for the residential–commercial sector: an application. Energy Policy; 2004 [in press].
[50] Utlu Z, Hepbasli A. Estimating energy utilization efficiency of the Turkish transportation sector by 2020. CD-Proceedings of the first international exergy, energy and environment symposium. 13–17 June, Izmir, Turkey, 2003; p. 533–38.
[51] Hepbasli A, Utlu Z. Evaluating the energy utilization efficiency of Turkey's renewable energy sources during 2001. Renewable Sustainable Energy Rev 2004;8(3):237–55.
[52] Ozdogan S, Arikol M. Energy and exergy analyses of selected Turkish industries. Energy 1995;20(1): 73–80.

[53] Wall G. Exergy—a useful concept. PhD Thesis, Göteburg (Sweden): Chalmers University of Technology; 1986.
[54] International Energy Agency (IEA). Key World Energy Statistics from the IEA. France; 2001.
[55] Brown HL, Hamel BB, Hedman BA, Koluch M, Gajanana BC, Troy P. Analysis of 108 industrial processes; 1985 (Library of Congress, Cataloging-In-Publication Data. Fairmount Press, Philadelphia).
[56] Wall G. Exergy flows through industrial processes. Energy 1988;13:197–208.